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NOCTURNAL URBAN BOUNDARY LAYER OVER CINCINNATI, OHIO

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ABSTRACT

Investigations of the nocturnal temperature and wind structure of the planetary boundary layer over a city were conducted in the Cincinnati, Ohio, metropolitan area. Temperatures near the surface were obtained by means of automobile traverses across the city, the vertical distributions of temperature were measured at several sites with a helicopter, and wind velocities were derived from pilot balloon observations.

Results of the investigations demonstrated a pronounced modification of the vertical temperature structure as air with a rural history traversed the city. The vertical extent of the modification, referred to herein as the "urban boundary layer," gradually increased with downwind distance over the urban area. Beyond the downwind side of the urban area, relatively unstable air was found aloft over a stable surface layer, suggesting a layer of outflowing urban air aloft that is called the "urban heat plume."

When a strong inversion existed in the planetary boundary layer upwind from the city, the urban boundary layer extended 150 to 300 ft above the surface. A superadiabatic lapse rate was observed within the urban boundary layer in the central business district and an isothermal lapse rate or weak inversion in the downwind suburban areas. A strong inversion, similar to that of the upwind rural environment, was maintained above the urban boundary layer.

1. INTRODUCTION

It is well known that the structure of the boundary layer over an urban area is modified from the structure that is observed in an upwind rural area. The modification results from mechanical turbulence generated by the movement of air over the large roughness elements of the urban area and thermal turbulence resulting from heat produced in the combustion of fossil fuels or stored in urban structures. The surface extent of the nocturnal urban-induced modification is well documented in the many "heat island" studies (e.g., Chandler, 1967; Mitchell, 1962; and Sundborg, 1950). Much less is known, however, about the vertical extent of the urban-induced modification, hereafter referred to as the urban boundary layer.

During nocturnal hours, the urban boundary layer normally can be delineated from vertical temperature profiles. Some effects of cities on their vertical temperature profiles can be seen in data from simultaneous wiresonde ascents over built-up and adjacent open areas described by Duckworth and Sandberg (1954) and from the instrumented helicopter soundings reported by Davidson (1967). Results of these studies indicate that the nocturnal urban boundary layer is considerably less stable than the air above adjacent rural areas, that multiple elevated inversions are sometimes present over cities, and that, in some cases, the air above cities is cooler than at the same height above adjacent rural areas.

From February 1967 through January 1968, the Division of Meteorology, National Air Pollution Control Administration, conducted 13 field investigations of the nocturnal urban boundary layer in the Cincinnati, Ohio, metropolitan area. The field investigations encompassed 1) surface temperature measurements across the city obtained by a sensor mounted on an automobile, 2) temperature measurements aloft based on coordinated helicopter soundings along the automobile route, and 3) pilot balloon observations in both urban and rural areas.

Before the field investigations were started, considerable thought was given to the shape that the urban boundary layer might reasonably be expected to have. The hypothesis that evolved is presented graphically in figure 1. A relatively unstable urban boundary layer develops as rural air flows over the city and is heated from below. The boundary layer gradually increases in height with downwind distance. Downwind of the city, a stable surface layer develops over the rural area and increases in height downwind. Above the stable surface layer is a layer of air that was previously modified by the urban surface but has not been influenced by the downwind rural surface. This configuration could result if the air were simply cooled from below as it passed out of the city and over the rural surface. However, Chandler (1960, 1961) substantiated the existence of an urban heat island circulation in which cool air near the surface moves across the fringes of a city toward the warmer central districts. The heat island circulation reinforces the inflow of air at the upwind edge of the city and tends to cause countergradient flow near the surface downwind of the city. The resulting convergence near the surface induces rising air motions over the city, divergence in the upper part of the urban boundary layer, and outflowing urban air above the stable surface layer downwind of the city. One might visualize this effect as a giant "urban heat plume" fanning out aloft downwind of the city.

Although the data presented in this paper are insufficient to prove the existence of the urban heat plume,

[1] On assignment from Environmental Science Services Administration, U.S. Department of Commerce

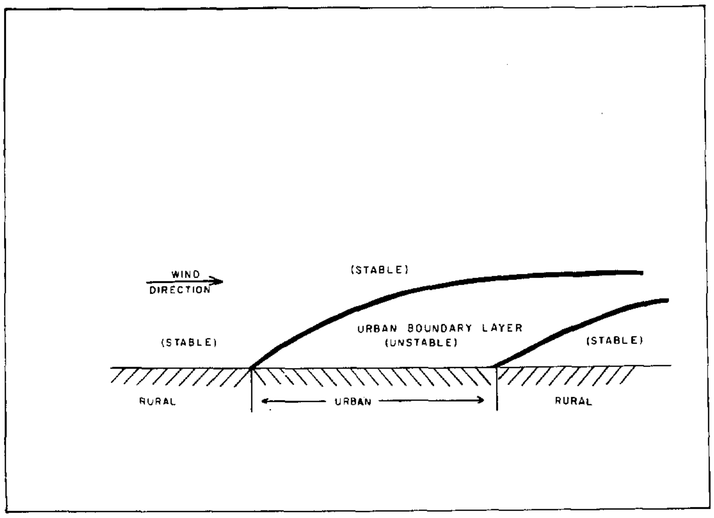

FIGURE 1.—Graphical presentation of urban boundary layer hypothesis.

they do support the hypothesis. In the interest of brevity, data for only six of the 13 field investigations are presented. The six are indicative of results of the total program.

2. TOPOGRAPHY AND LAND USE

Cincinnati is situated on the Ohio River about 16 mi east of the Ohio-Indiana border. The metropolitan area, which includes parts of northern Kentucky, is situated on an upland plain through which Mill Creek and the Little Miami and Licking Rivers have carved out broad valleys (fig. 2). Downtown Cincinnati is located in a basin formed by junctions of Mill Creek and the Licking River with the Ohio River. Steep bluffs rise 200 to 400 ft from the basin and river valley floors to the general level of the plateau, about 900 ft MSL.

The downtown business district is located in the eastern portion of the basin. Dense residential and light commercial activity fill the remainder of the basin and the western and central portions of the plateau between the downtown area and Norwood Trough. Newer and less dense residential areas occupy the hilltops surrounding the basin and valleys. Industry is concentrated in Norwood Trough and Mill Creek Valley. The population of the urban area is about one million.

3. INSTRUMENTATION

Basic instrumentation for the study consisted of two telethermometers: a Yellow Springs Model 43TE telethermometer [2] mounted on an automobile to obtain surface temperatures (5.5 ft above the surface), and a telethermometer of "local" design and construction mounted on a helicopter to obtain vertical temperature

[2] Mention of commercial products does not constitute endorsement.

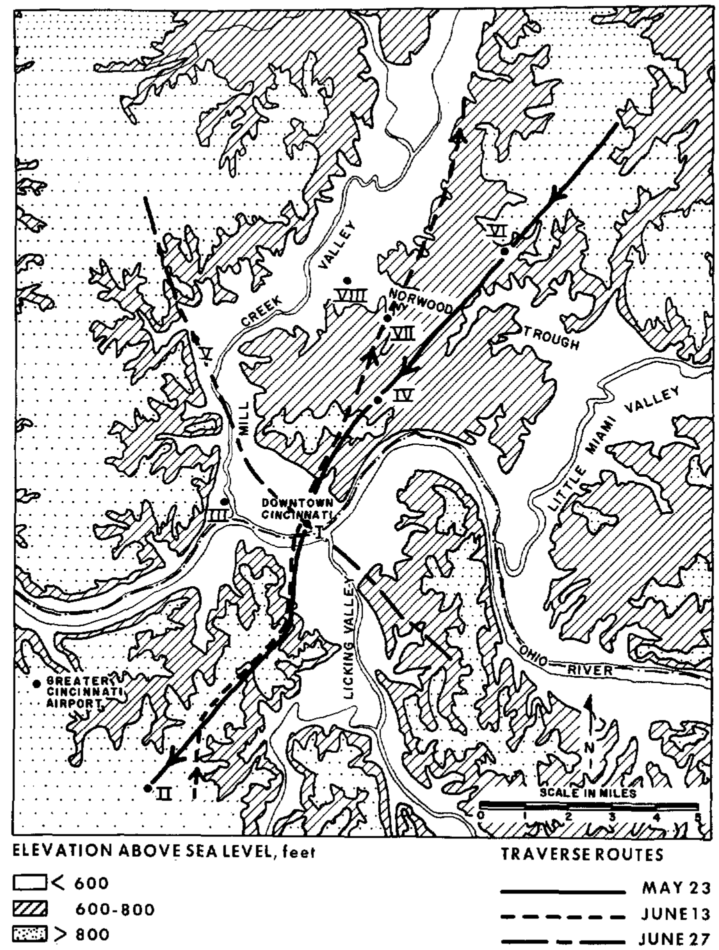

FIGURE 2.—Topography map of the Cincinnati, Ohio, area showing traverse routes. Roman numerals indicate helicopter sounding and pilot balloon observation sites; these correspond to the profiles given in figures 3, 6, and 7.

profiles. Measurements from both instruments were recorded manually.

The telethermometer used with the helicopter consists of a thermistor in a Wheatstone bridge circuit. The resistance in the thermistor is indicated on a meter calibrated against a mercury-in-glass thermometer. Readability of the meter is 0.16°F. The absolute accuracy of the instrument is estimated to be about 0.5°F, and the time constant is roughly 4 sec.

The thermistor probe was housed midway in a radiation shield consisting of two concentric aluminum tubes with radii of ¾ and 1¼ in. separated by ½ in. of styrofoam insulation. The probe was mounted on a skid of the helicopter, and sampling was conducted at a forward speed of 40 to 60 mi hr^{-1} to minimize the effect of induced air movement from the rotor. Temperature and altitude were recorded after a level traverse of 13 sec (about ¼ mile) at the selected altitude and location to allow for lag in the response of the thermistor.

The Yellow Springs instrument also utilizes a thermistor in a Wheatstone bridge circuit. As the resistance of the thermistor changes, circuit imbalance is indicated on a meter calibrated for direct temperature readout. Absolute accuracy of this instrument is 1.2°F, readability is to 0.5°F, and the time constant is roughly 1 sec. The thermistor was housed in a radiation shield (similar to that just described), which was attached 3½ ft above and about 8 in. forward of the front bumper of the automobile. Ventilation was provided by the forward motion of the automobile; measurements were taken at speeds of 25 to 40 mi hr^{-1}, away from traffic congestion. A fan was attached to the radiation shield to provide ventilation when the vehicle was not in motion so that this instrument could be compared with the telethermometer used with the helicopter and also with a standard mercury thermometer. The instruments were compared in this manner before each field investigation.

4. EXPERIMENTAL PROCEDURES

The field investigations were conducted from about 45 min before sunrise to 15 min after sunrise, along a route traversing the metropolitan area from rural environs through the central business district. The short time period of investigation was dictated by the desirability of obtaining measurements during relatively steady meteorological conditions and by the danger of helicopter operation at low altitudes in complete darkness. The traverse routes were selected roughly along the path of airflow over the urban area. Consideration was given, however, to the gradient flow and available surface wind observations and to available auto routes and helicopter sounding locations within the metropolitan area.

The automobile sampling team was dispatched about 3 hr before sunrise and made three to four traverses over the route. The temperature data obtained from the automobile traverses were plotted on a chart of time versus distance and were analyzed so that the temperature could be determined at any time or location along the route by interpolation. The helicopter team was dispatched about 45 min before sunrise and usually took temperature soundings at several elevations above five locations along the route, normally at an upwind and a downwind rural site and at three urban locations. The first height above the ground at which a temperature reading was obtained was dictated by the available light and by terrain features. Readings were obtained 10 ft off the ground in certain rural locations. The elevation of lowest temperature reading in urban areas ranged from 50 to 200 ft above ground. The surface temperature readings obtained from the automobile traverses were used to extend the helicopter temperature soundings to the surface.

Several single-theodolite pilot balloon observations were made during each field investigation at one to three locations, usually along the selected traverse route. Ten-gram balloons were used, and readings were taken every 20 sec.

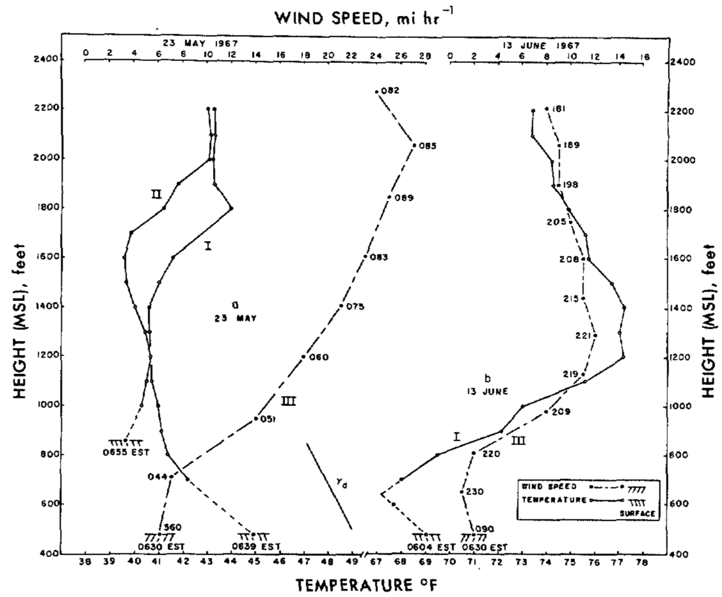

FIGURE 3.—Vertical temperature and wind profiles for May 23 and June 13. Roman numerals indicate locations on figure 2 where the profiles were obtained. Wind direction is given in degrees for each level on the wind profile. That portion of the temperature profile interpolated from the automobile temperature traverses is indicated by a dashed line.

5. RESULTS

During the first field investigation, May 23, 1967, a high-pressure system of continental polar origin, whose center was located over Lake Ontario, extended southeastward toward the junction of the Ohio and Mississippi Rivers. The pilot balloon measurements over Cincinnati showed that winds were northerly at about 6 mi hr^{-1} near the surface and became northeasterly aloft with a minimum speed of 27 mi hr^{-1} at 2,050 ft MSL (fig. 3, profiles a). Temperature measurements from the automobile and helicopter soundings were conducted on a route crossing the city from northeast to southwest (fig. 2).

A cross section of the temperature structure over Cincinnati on May 23 is shown in figure 4. In the rural area upwind of the city (right-hand side of the cross section), a weak inversion extended to 1,500 ft MSL. Above this level, a moderate inversion extended to 1,800 ft MSL. The urban boundary layer had begun to develop above the upwind surburban area and gradually increased in height with downwind distance over the city. A superadiabatic lapse rate occurred in the lower 200 ft of the urban boundary layer with an adiabatic to isothermal lapse rate above to the interface of the urban boundary layer. In the vicinity of the central business district, the urban boundary layer extended roughly 800 ft above the surface.

Downwind from the city, a stable layer of air was observed near the surface, while above it an adiabatic layer, presumably the downwind propagation of the urban

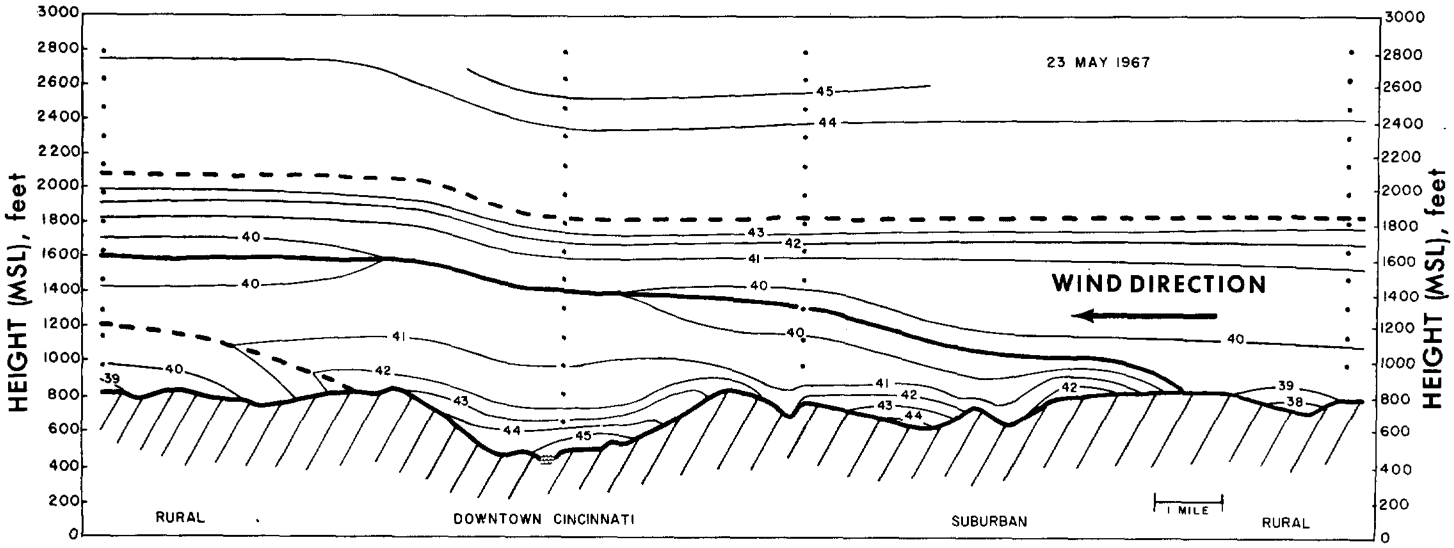

FIGURE 4.—Cross section of temperature structure for May 23. The top of the urban boundary layer is indicated by the heavy solid line. The dashed lines indicate a temperature discontinuity with less stable air above. The dots alined vertically show the locations where helicopter temperature measurements were obtained.

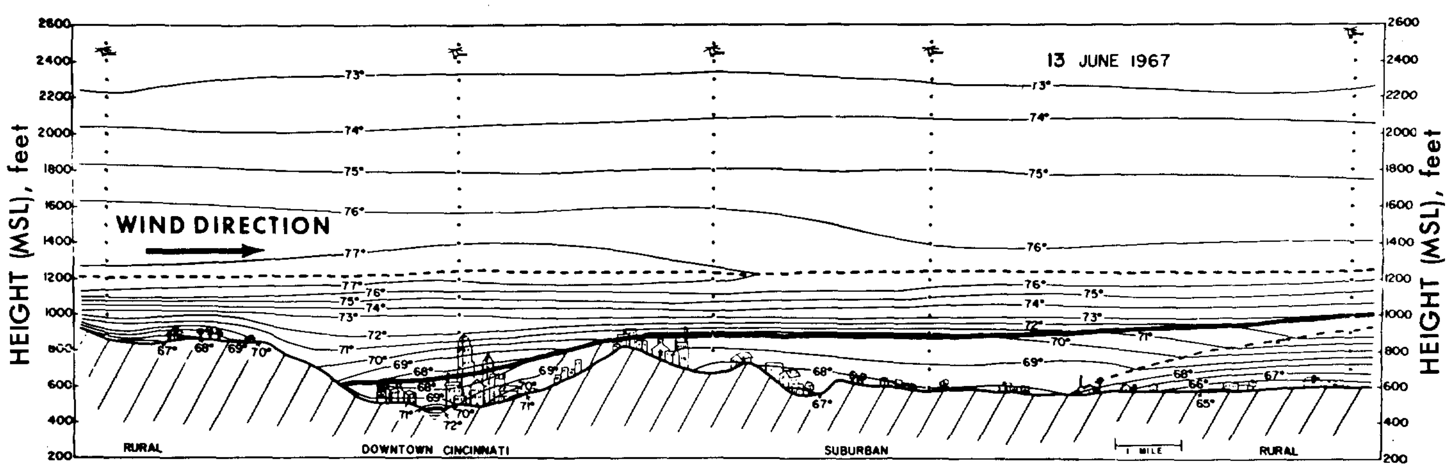

FIGURE 5.—Cross section of temperature structure for June 13. The top of the urban boundary layer is indicated by the heavy solid line. The dashed lines indicate a temperature discontinuity with less stable air above. The dots alined vertically show the locations where helicopter temperature measurements were obtained. The schematic representation of the height of the buildings is roughly to scale.

mixed layer, extended to the base of the moderately stable layer aloft (see also fig. 3, profiles a, sounding II). The top of the moderately stable layer aloft was nearly level except downwind from the city, where it was elevated slightly. This increase was attributed to the air rising as it encountered a hill on the Kentucky side of the Ohio River, rather than to the occurrence of organized convergence over the warm city.

The cross section for June 13, 1967, presented in figure 5, is typical for the field investigations conducted when a strong surface-based inversion existed in the boundary layer above the rural area upwind of the city. A quasi-stationary high-pressure center prevailed off the east coast. A weak southerly airflow dominated the Ohio Valley. Surface-temperature measurements and helicopter soundings were conducted on a route traversing the city from southwest to northeast (fig. 2). A very strong surface-based inversion extended to about 1,200 ft MSL in the rural area upwind from the city (left-hand side of the cross section). The urban boundary layer had begun to form above the urban area on the Kentucky side of the Ohio River and extended through the suburban areas downwind from the city. In the central business district, the urban boundary layer consisted of a superadiabatic layer extending to about 150 ft above the surface. In the downwind suburban areas, the boundary layer consisted of a weak inversion that generally increased in height with downwind distance. The lowest vertical extent (above ground) of the boundary layer was over the ridge north of the central business district. Although the boundary

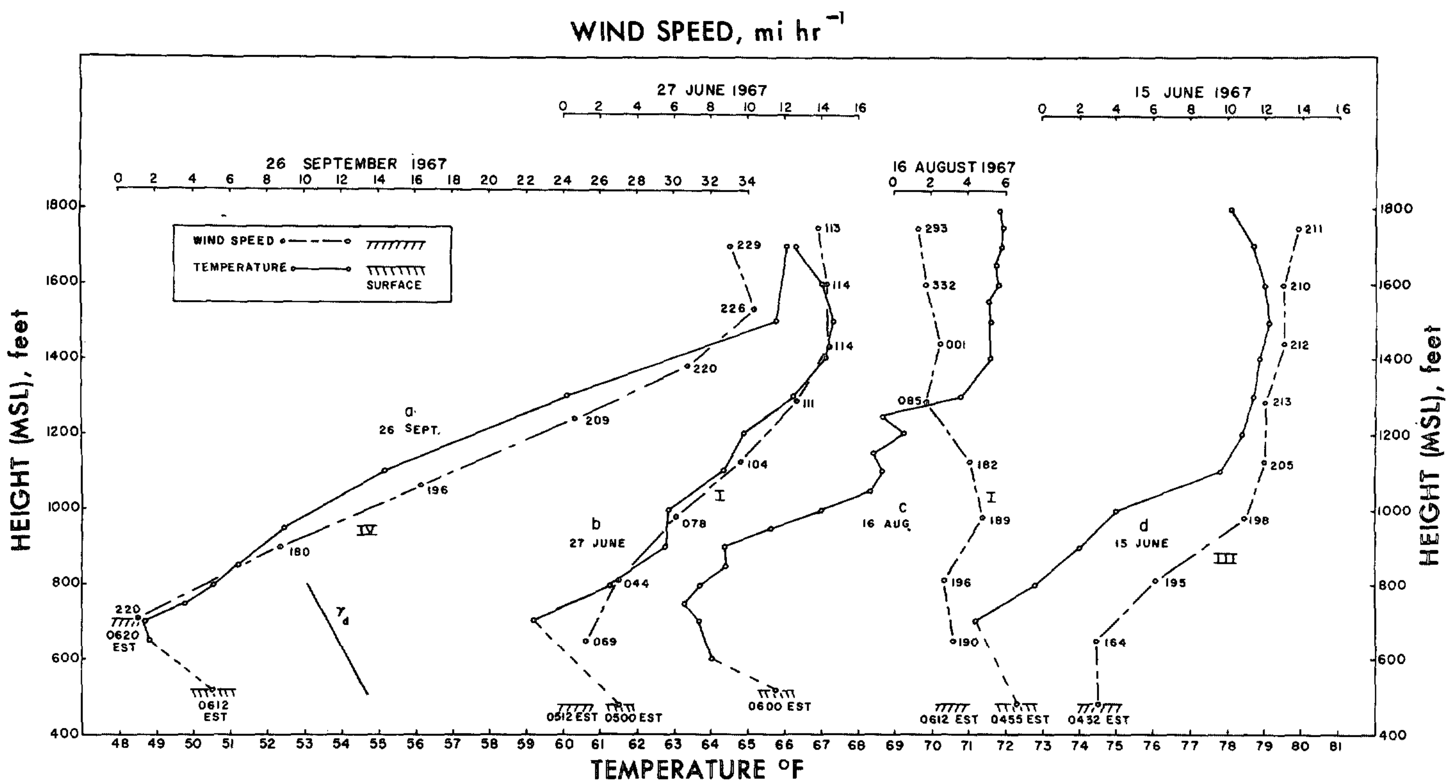

Figure 6.—Vertical temperature profiles obtained in the vicinity of the central business district (Roman numeral I on fig. 2) and associated wind profiles. Roman numerals indicate the locations on figure 2 where the wind profiles were obtained. Wind direction is given in degrees at each level of the wind profiles. That portion of the temperature profile interpolated from the automobile temperature traverses is indicated by a dashed line.

layer tended to follow the contour of the land on the windward side of the ridge, it did not do so on the leeward side. A moderate to strong inversion existed above the entire extent of the urban boundary layer.

The wind and temperature profiles obtained near the central business district are presented in figure 3, profiles b. The wind speed within the boundary layer was generally low and exhibited little vertical shear. It is not known whether this is characteristic of the urban boundary layer or is due in part to shielding by the surrounding ridges. Above the boundary layer the wind speed increased to a maximum near the top of the inversion.

A very stable surface stratum was observed over the rural area downwind from the city. Above this was a layer of air with a temperature profile similar to that of the urban boundary layer in the adjacent suburban area. It is suggested that this layer aloft downwind of the city was a region of outflowing urban air; it is termed the "urban heat plume."

The boundary between the urban heat plume and the very stable air below (over the rural area) probably develops slowly throughout the night. By sunrise the boundary resembles a quasi-stationary front with the relatively warm urban air flowing out aloft over cooler rural air. Mixing probably occurs at the interfaces, particularly the upper interface as the urban heat plume becomes warmer with distance downwind.

Temperature profiles in the vicinity of the central business district and associated wind profiles for four other field investigations, conducted on mornings when a strong surface-based inversion prevailed over the rural area upwind of the city, are presented in figure 6. The temperature and wind profiles within the urban boundary layer are similar to those obtained on June 13 (fig. 3, profiles b). They demonstrate a consistency of the urban boundary layer with similar conditions in the boundary layer above the rural area upwind of the city.

Temperature profiles downwind from the central business district for five "stable" cases are shown in figure 7. Temperature often increases slightly with height within the urban boundary layer. However, a discontinuity of the lapse rates within and above the urban boundary layer is indicated in all cases. Two of the profiles, those of June 27 (fig. 7, profile b) and August 16 (fig. 7, profile c), warrant further comment. On August 16, in contrast to other stable cases, the temperature profile in the boundary layer of the downwind suburban and valley areas was nearly adiabatic. Although the physical processes within the boundary layer are not well understood, one unusual feature was obvious. The winds were extremely light

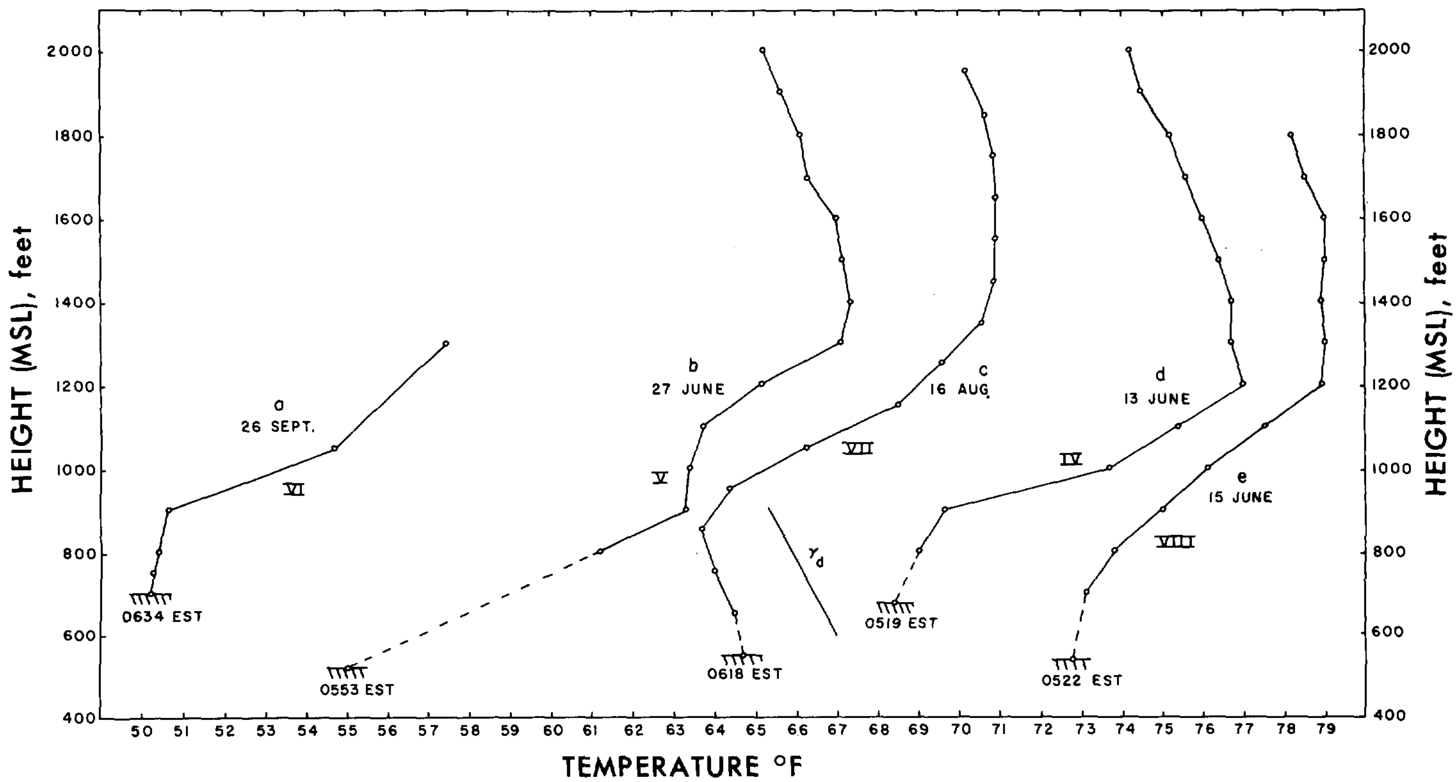

FIGURE 7.—Vertical temperature profiles obtained in the downwind suburban areas of the city. Roman numerals indicate the locations on figure 2 where the profiles were obtained. That portion of the profile interpolated from the automobile temperature traverses is indicated by a dashed line.

and variable through a deep layer (fig. 6, profiles c), suggesting a relatively long residence time of the air within the urban area and little mechanical turbulence.

The temperature profile for June 27 (fig. 7, profile b) was obtained in a moderately dense residential and industrial area on the western side of Mill Creek Valley. The strong inversion from the surface to 900 ft MSL is attributed to drainage of cold air into the valley from higher elevations. The weak inversion from 900 to 1,100 ft MSL is believed to be the urban heat plume.

Temperature data from this profile are included in the cross section presented in figure 8 (first sounding on the left). Surface temperature measurements and helicopter soundings were obtained on a route traversing the city from southeast to northwest (fig. 2). The winds between 900 and 1,100 ft MSL were generally normal to the cross section (fig. 6, profiles b). In this case, the heat plume consisted of relatively warm urban air advected from the higher elevations north of the central business district over a cool drainage flow in the valley.

6. DISCUSSION

Owing to the complex topographic features of the Cincinnati metropolitan area, data presented in this paper are not amenable to explicit conclusions about the nature of the urban boundary layer. Many features among the data were consistent, however, and suggest the occurrence of orderly physical processes. These features are discussed below.

The first relates to Summers' mathematical model (1965) of the urban boundary layer. Summers developed a simple model in which an adiabatic mixing layer of increasing depth builds up because of accumulation of heat as air with a rural history traverses an urban area. The increasing height of the mixing layer, from the upwind edge to the center of the city, was determined as a function of the lapse rate of the planetary boundary layer upwind from the city, the heat sources within the city, and the average wind speed within the boundary layer. The results of the present study support Summers' choice of parameters in two respects. First, the height of the urban boundary layer over Cincinnati appears to be related to the lapse rate of the planetary boundary layer upwind of the city. Second, with a strong inversion over the rural area upwind of the city, the urban boundary layer appears to result primarily from the addition of heat within the urban area rather than from mechanical turbulence generated by the wind passing over the large roughness elements of the city. Even with extreme wind shear above the city, as was observed on September 26 (fig. 6, profiles a), the boundary layer in the vicinity of the central business district was not noticeably different from that of August 16, a day with very light winds (fig. 6, profiles c).

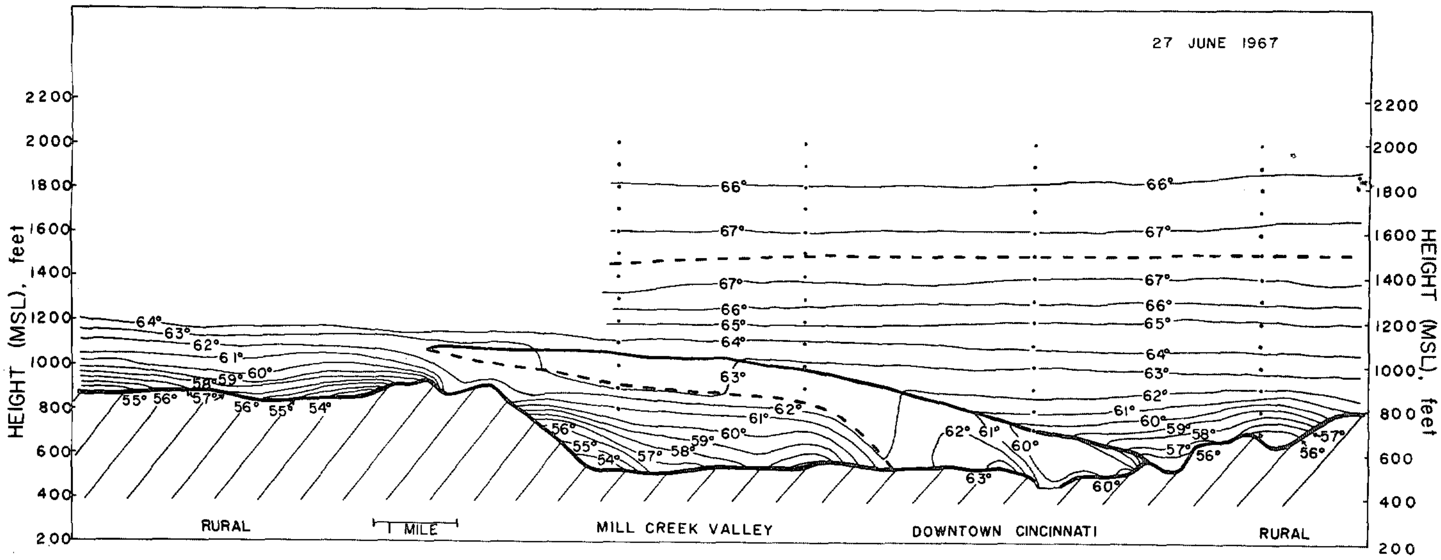

FIGURE 8.—Cross section of temperature structure for June 27. The top of the urban boundary layer is indicated by the heavy solid line. The dashed lines indicate a temperature discontinuity with less stable air above. The dots alined vertically show the locations where helicopter temperature measurements were obtained.

On both these occasions, as with the other stable situations, the urban boundary layer over the central business district was characterized by light winds and an absence of both wind shear and apparent turbulence. The flow above the urban boundary layer appeared divorced from general flow near the urban surface. There was, however, a consistent flow or drift within the boundary layer. This was noted on several occasions when pilot balloon wind observations were obtained in the urban and downwind suburban areas and on one occasion when neutral lift balloons were released and visually tracked from several locations in the urban and suburban areas.

With a weak inversion upwind of the city (e.g., fig. 4) Summers' model does not apply; some of the recorded temperatures were lower aloft over the city than those observed at the same height (MSL) over the rural area, suggesting the turbulent destruction of an elevated inversion. In such cases, wind-generated turbulence is an important factor in the formation of the urban boundary layer.

The urban boundary layer was sufficiently shallow during the stable cases (e.g., see fig. 5) that two distinct urban dispersion regimes must be acknowledged. These are the relatively unstable regimes within the urban boundary layer (i.e., adjacent to the surface) and the stable stratum immediately above. Current knowledge of diffusion suggests that pollutants emitted within the boundary layer will be dispersed through and essentially contained within the boundary layer. This study, however, has demonstrated a spatial variation of the temperature profiles within the urban boundary layer and consequently a spatial variation of the dispersion rate.

Pollutants emitted from tall stacks into the stable stratum above the boundary layer will experience little vertical dispersion. They will not contribute significantly to the ground-level concentration at a nearby receptor, and possibly not anywhere over the urban area, until the fumigation or inversion breakup period that typically occurs near midmorning. This concept is illustrated in figure 9, which is a photograph of a smoke plume within the stable stratum above downtown Cincinnati. The photograph was obtained on the morning of August 16, simultaneously with the sounding given in figure 6, profiles c. The smoke plume was in the layer that extended from 1,100 to 1,300 ft MSL and was penetrated by the helicopter. Radiational cooling of the dense plume, an additional complicating factor of the urban temperature structure, may be responsible for the discontinuity of the temperature profile in that layer; the discontinuity was not observed in later downwind temperature soundings.

The concept of the urban heat plume, although not wholly substantiated by any of the field investigations, is nourished by many bits of data. Foremost are the temperature profiles in the rural area downwind of the city. On several occasions these have indicated a less stable layer of air aloft between the very stable stratums of the rural surface layer and that existing above the urban boundary layer. On one occasion, an area of outflow aloft of urban air was identified by use of a neutral lift balloon. The balloon, released near the surface downwind of the central business district, drifted toward the northwest. As it approached the bluff on the western side of Mill Creek Valley, it rose abruptly. Once above the bluff, it moved out rapidly toward the north with the general flow above the urban boundary layer.

7. SUMMARY

Results of field investigations in the Cincinnati, Ohio, metropolitan area indicated that a relatively unstable urban boundary layer develops as rural air flows over the city. The boundary layer gradually increased in height with downwind distance over the city. Beyond the down-

FIGURE 9.—Smoke plume within the stable stratum above the urban boundary layer, Aug. 16, 1967.

wind edge of the urban area, relatively unstable air was found aloft between the more stable stratums of the rural surface layer downwind from the city and the layer of air above the urban boundary layer. It is suggested that this unstable air aloft was an area of outflowing urban air. It is called the urban heat plume.

With a strong inversion in the planetary boundary layer upwind from the city, the urban boundary layer was sufficiently low that two distinct urban dispersion regimes must be acknowledged. These are the relatively unstable boundary layer and the stable stratum immediately above.

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